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LASER WELDING OF NAVY SHIP CONSTRUCTION MATERIALS

UNITED AIRCRAFT RESEARCH LABORATORIES

PREPARED FOR

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LASER WELDING OF NA[illegible]
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Final Report

(June 30, 1972 to June 30, 197[illegible])

August 30, 1973

By

CONRAD M. BANAS

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13. ABSTRACT

The results of an experimental laser welding program directed toward establishing the feasibility of laser welding in the fabrication of high speed surface vessels are reported. Data are presented for laser welds formed in 1/4 in. thick HY-130 steel, 1/16 in. thick HY-180 steel, 1/8 and 1/4 in. thick Ti-6Al-4V titanium alloy and 5456 aluminum alloy. It is shown that high quality welds with properties equivalent to, or better than, those of the parent material can be obtained with appropriate selection of welding parameters. It is concluded that further studies are warranted to explore the nature of high yield strength steel refinement during laser welding, to examine the effects of laser welding parameters on grain growth in titanium alloys and to investigate the potential of laser welding for heat-treatable aluminum alloys requiring the utilization of filler material.

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i

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iii

Report M911502-6

Laser Welding of Navy Ship Construction Materials

TABLE OF CONTENTS

Report M911502-6

Laser Welding of Navy Ship Construction Materials

SUMMARY

An experimental investigation was conducted of laser welding of Navy ship construction materials. Bead-on-plate penetrations were formed in 1/4-in.-thick HY-130 steel, 1/16-in.-thick HY-180 steel, 1/8- and 1/4-in.-thick Ti-6Al-4V titanium alloy and in 1/8-in.-thick 5456 aluminum alloy. Continuous carbon-dioxide laser power levels to 8 kW were used; welding speed was varied from 20 to 180 ipm in order to establish appropriate welding parameters. The bead-on-plate penetrations were initially screened by visual, metallographic, NDT and mechanical tests and then forwarded to NSSC for more detailed evaluation.

Demonstration butt and lap weld specimens were formed at a CO_2 laser power level of 5.5 kW in the materials and thicknesses noted above. Weld parameters for these welds were selected on the basis of bead-on-plate evaluations and ranged from 50 ipm in 1/4-in.-thick material to 160 ipm in 1/16-in.-thick material. Demonstration weld specimens were inspected visually, X-rayed and then forwarded to NSSC for final evaluation. The finished samples, which were 5 x 7 in. in size, exhibited excellent top and bottom surface bead characteristics and defect-free fusion zones.

This program was undertaken under the sponsorship of the Naval Ship Systems Command under Contract N00024-72-C-5585.

INTRODUCTION

At the outset of the experimental program described herein, carbon-dioxide lasers had been developed with continuous output power levels in the multikilowatt range (Refs. 1, 2). Deep-penetration welding, similar to that achieved with electron beam equipment, had been demonstrated in a number of representative materials (Refs. 3-6). Further, high-speed laser welding of thin gage materials with a minimum of thermal energy input and distortion had been demonstrated (Ref. 7), and inspection had shown that high-quality laser welds could be formed with excellent metallographic and mechanical properties.

The encouraging results noted above together with the versatility of the laser indicated a promising potential for laser utilization in shipyard welding. It was therefore proposed that laser welding experience be extended to include materials of interest for shipbuilding. The proposed program received the support of the Naval Ship Systems Command and was initially directed toward generation of laser welds in high yield strength steels. At NSSC request, the program was then broadened to include titanium and aluminum alloys specified by the Navy for potential use in the construction of high-speed surface vessels.

It was the objective of the program described herein to establish appropriate weld parameters for the materials of interest and to generate sample welds for evaluation by the Navy. Overall results of the program were expected to provide the basis for an initial evaluation of the potential of laser welding for ship construction.

EXPERIMENTAL APPARATUS AND PROCEDURE

Laser Systems

Tests were conducted primarily with a 6 kW, coaxial laser system developed under a Corporate-sponsored program at the United Aircraft Research Laboratories. This system, shown in Fig. 1 and similar to that described in Ref. 1, utilizes high mass flow recirculation of laser gases to effectively remove waste heat and provide efficient high-power operation.

The 6 kW, carbon-dioxide laser system operates in a master-oscillator, power-amplifier (MOPA) configuration. A Coherent Radiation Laboratories, Model #41, CO_2 laser with a Gaussian output beam is utilized to drive the amplifier, which is comprised of twelve discharge tubes arranged electrically in parallel and optically in series. High fidelity amplification is achieved such that the Gaussian energy

distribution of the 100 watt input beam is reproduced in the 6 kW maximum output beam. The high optical quality provided by this system results in maximum focusability and effective utilization of laser power.

Limited tests were also conducted at the 8 kW level with a cross-beam laser developed under NOSC/NOL Contract No. N60921-70-C-0219. This unit, described in Ref. 2 and shown in Fig. 2, also operates in the MOPA configuration and utilizes a combination of DC and RF power to provide stable operation in a single large channel. In this unit the gas flow and electric discharge are collinear while the laser cavity is transverse to the flow direction. This higher-power laser system had been slated for more extensive utilization under the initial program objective, which was directed toward thicker materials; redirection of the program to materials suitable for high-speed surface vessel fabrication, however, rendered primary use of the lower-power system more effective.

Focusing Optics

The amplified beam was focused by a spherical mirror positioned to provide downhand welding, as shown in Fig. 3. The focusing mirror was fabricated of copper which was polished to provide a reflectance at 10.6 microns (the laser wavelength) greater than 98%. Water-cooling of the copper substrate was provided to prevent thermal distortion. Beam offset to provide clearance for welding was held to less than 6 degrees in order to minimize spherical aberration. A 30-in.-focal-length mirror was used with the 6 kW system; the effective f/number for an output beam diameter of 2.6 in. was 11.5. A 20-in.-focal-length mirror was used with the 1.75-in.-diameter beam from the higher-power system so that f/11.5 focusing pertained to this system also.

Gas Shielding

Since all of the materials welded during the program are sensitive to atmospheric contamination during the welding process, provisions were made for shielding the welds from the atmosphere. As may be noted in Fig. 4, the gas shield utilizes both a top surface trailer through which the laser beam passes and a subsurface shield. In addition to preventing weld contamination, the top surface shield serves to remove metal vapor ions from the laser beam path and thereby prevent optical breakdown in the region above the workpiece. Without such provision, a plasma is formed above the workpiece; this plasma absorbs most of the beam energy and prevents effective welding.

Helium at a flow rate of the order of 20 cfh was supplied to the beam transmission region of the shield to provide maximum suppression of plasma formation. Argon, which is more effective for shielding due to its higher molecular weight,

was supplied to the trailer and the subsurface at flow rates of the order of 30 cfh. Visual, metallographic and limited chemical analysis of the fusion zones indicated that the shielding provisions were quite adequate for the welding conditions and materials used. Further, energy considerations showed that plasma formation had been suppressed and that essentially 100% beam energy transmission to the workpiece had been effected.

Material

Sample material for the weld tests was supplied by NSSC. The material included 1/4-in.-thick HY-130 steel, 1/8- and 1/4-in.-thick Ti-6Al-4V titanium alloy, 1/16-in.-thick HY-180 steel and 1/8-in.-thick 5456 aluminum alloy. A listing of these materials together with their composition and properties if presented in Table I.

Weld samples were cut to 3 1/2 x 6 in. in size. Heavy surface coatings and oxides were machined off and one 6-in. edge was milled square for close butt weld fitup. No filler material was used for any of the joints formed.

Test Procedure

Titanium alloy samples were acid cleaned in a 20% HNO_3, 2% HF solution prior to welding. Aluminum alloy samples were scraped immediately prior to welding. All weld samples were cleaned with acetone immediately before joining.

Test samples were placed in the welding fixture shown in Fig. 4 and aligned with the beam. Laser spot welds were then made at the ends of the weld specimens to prevent joint separation during welding and to insure that the joint was properly aligned with the focused beam. Due to the narrow fusion zone effected at high welding speeds, alignment was carefully performed to insure good joint properties. Finished butt weld samples were trimmed to approximately 5 x 7 in. to remove the laser spot welds at the ends, together with the on-off portions of the weld zone which would normally be intercepted by run-off tabs. Steel and aluminum specimens were delivered to NSSC in the "as-welded" condition. Titanium alloy specimens were stress-relieved in vacuum for two hours at 1000 F to remove thermal stresses induced during the welding process. Post-weld stress relief is standard practice for titanium alloys and appears essential to laser welds as well.

DISCUSSION OF EXPERIMENTAL RESULTS

Bead-on-Plate Penetrations

Bead-on-plate penetrations were initially formed in the test materials in order to establish weld parameters as well as to assess requirements for gas shielding. Sixty bead-on-plate penetrations, generated at power levels to 8 kW, were formed. Fifty-six bead-on-plate penetrations, as noted in Table II, were forwarded to NSSC for evaluation which served as the basis for selection of butt weld parameters for demonstration welds.

Additional bead-on-plate penetrations were formed for preliminary evaluation at UARL. Typical are the bead-on-plate results for 5456 aluminum alloy shown in Fig. 5. It is noted from comparison of the cross sections shown that the width of the fusion zone decreases as welding speed is increased at constant power level. Variations in the shape of the fusion zone are also to be noted in Fig. 5. Such variations were less pronounced for aluminum than for the other test materials, apparently a result of its higher thermal diffusivity.

Also evident in Fig. 5 is the existence of substantial porosity in the fused zone. In aluminum welds such porosity is most often due to the presence of hydrogen which may stem from traces of water in the weld region. These results for aluminum, together with somewhat similar experience with titanium and to a lesser degree with the high-yield-strength steels, indicated that more stringent pre-weld cleaning procedures than those used in the initial tests were required and that additional attention to gas-shielding provisions was necessary.

Weld Parameter Selection

Evaluation of bead-on-plate cross sections at NSSC and UARL by metallographic, visual, NDT and limited mechanical tests resulted in the selection of the following conditions for butt-weld fabrication. A laser power level of 5.5 kW was chosen with welding speeds of 50 ipm in 1/4-in.-thick material, 100 ipm in 1/8-in.-thick material, 160 ipm in 1/16-in.-thick material and 140 ipm for a burn-thru lap weld in 1/16-in.-thick material. It is perhaps surprising that selected welding speeds did not vary with the nature of the material; this behavior, however, is felt to be coincidental and should not be construed as a laser welding guideline.

In accordance with requirements for weld-sample cleanliness exceeding that obtained in the bead-on-plate penetrations, all butt weld samples were surface-machined to remove oxides and coatings. Immediately prior to welding, titanium alloy specimens were further cleaned in a solution of 20% HNO_3, 2% HF acid solution, aluminum alloy specimens were scraped and all samples were cleaned with acetone.

It was found that these added precautions, together with appropriate selection of gas-shielding parameters, led to substantial improvements in weld zone cleanliness. It was further found that properly prepared butt-weld specimens exhibited fusion zones essentially indistinguishable from bead-on-plate penetrations.

Typical of the results of butt-weld preparation is that represented by the HY-130 specimen shown in cross section in Fig. 6. The weld cross section, which was prepared at 100 ipm at 5 kW, exhibits unusual features which are a direct consequence of the unique characteristics of the laser welding process. Due to the deep-penetration effect, the energy deposition in this thin material was apparently nearly uniform throughout the material depth. Lateral heat conduction into the base material occurs in the central portion of the material leading to a restriction in the fused zone extent and a "dumbbell-shaped" fusion zone. This behavior is attested by the columnar solidification grains along the lines of maximum thermal gradient exhibited in Fig. 6.

X-ray evaluation of the weld zone, as shown in Fig. 7, indicated no evidence of porosity. Tensile tests of portions of the weld resulted in failure in the base material well outside the fusion and heat-affected zones (Fig. 7). It is to be noted, however, that the ultimate tensile strength measured in these tests was somewhat lower than that anticipated for HY-130 material. This reduced strength was apparently characteristic of the specific material supplied for the program. Finally, it was found that the welds could readily withstand guided face and root bends to a radius equivalent to three times the material thickness.

Demonstration Weld Samples

HY-130 Steel

Final sample welds delivered to NSSC for evaluation are listed in Table III and shown in Figs. 8-13. Figure 8 shows a butt weld in 1/4-in.-thick HY-130 steel fabricated at 50 ipm at a laser power level of 50 ipm. The top surface weld bead presents a smooth shiny appearance. An X-ray of the weld zone, also shown in Fig. 8, shows that no porosity or defects exist in the region.

Limited mechanical tests of similar HY-130 welds at UARL showed a tensile strength in the weld zone greater than that of the parent material. Failure in the test specimens occurred well outside the fusion and heat-affected zones. Guided root and face bend tests to a radius equivalent to three times the material thickness were successfully met by the weld samples. A sample weld also withstood a one-times-thickness radius unguided bend test performed at NSSC. In this latter case no evidence of failure was indicated in spite of extreme stress concentration at the edge of the weld which occurred during the test.

The results in HY-130 welds were of sufficient interest so that more detailed evaluation was undertaken under Corporate sponsorship, as reported in Ref. 8. In these tests it was found that the Charpy impact strength of the weld material was higher than that of the parent material, in some cases by as much as 50%. An initial conclusion that the increased ductility might be due to softening of the material during welding was obviated by hardness measurements, which showed the weld material to be harder than the base. Further study of the weld material by chemical and scanning electron microscope analysis showed that the oxygen content of the material in the fusion zone had been significantly reduced (by as much as 50%) during the laser welding process and that the shape of the inclusions had been modified. With respect to the latter, the stringer-shaped inclusions which were oriented preferentially in the rolling direction were somewhat spheroidized during welding. The refinement of HY-130 steel during laser welding is assumed to have been instrumental in the increase in weld material ductility over that of the parent material. This is an extremely significant finding which warrants further detailed investigation as applied to metals with varying degrees of impurities.

HY-180 Steel

Lap and butt weld specimens in HY-180 material are shown in Figs. 9 and 10. The high welding speeds at which these welds were made, 160 ipm for the butt weld in Fig. 9 and 140 ipm for the lap weld in Fig. 10, resulted in a smooth, defect-free fusion zone. In addition to the X-ray information shown in Figs. 9 and 10, bend and tensile tests were performed on samples taken from the trimmed ends of the demonstration welds. It was found that the welds were stronger than the parent material in tension and that the welds could readily withstand a 3-times-thickness radius bend test. While chemical analysis was not performed on HY-180 specimens, the test results indicate that atmospheric contamination was effectively prevented during the welding process.

Ti-6Al-4V

Titanium alloy weld specimens are shown in Figs. 11 and 12. Weld beads in this material exhibited a shiny metallic surface without any traces of discoloration. X-ray evaluation of the welds, as shown in Figs. 11 and 12, also attested the soundness of the welds. Slight traces of metal spatter were noted on the lower surfaces of some welds, especially at lower welding speeds; this may be noted in the X-ray photograph shown in Fig. 11.

Titanium tensile test specimens taken from the trimmed ends of the demonstration samples failed at the edge of the weld fusion zone at a stress level approximately equal to that of the ultimate tensile strength of the base material. It was found that as-welded specimens, as expected, were quite brittle, but that standard stress relief for 2 hours at 1000 F was sufficient to eliminate this brittleness. Another factor which was noted was the tendency for undercutting at the edge of the

fusion zone in titanium welds. This tendency was reduced as pre-weld cleaning procedures were made more stringent but bears further investigation relative to its potential effect on fatigue endurance.

5456 Aluminum Alloy

The aluminum alloy demonstration weld is shown in Fig. 13. The weld, formed at a speed of 100 ipm, exhibits a smooth, clean, uniform appearance without evidence of porosity or defects. As in the case for titanium, some tendency for lower surface spatter was found.

Tensile test specimens obtained from the trimmed edges of the demonstration aluminum welds failed in the weld zone at a stress level of 50,000 psi, essentially equal to that of the ultimate tensile strength of the parent material. The weld failure extended diagonally across the weld from the top corner of the fusion zone to the opposite lower surface corner. The demonstration weld samples readily passed a 3-times-thickness radius guided bend test.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the results of the experimental laser welding program described herein, it is concluded that direct laser butt-welding of the high-yield-strength steels, Ti-6Al-4V titanium alloy and 5456 aluminum alloy in thicknesses suitable for high-speed surface vessel fabrication is a highly feasible process. It is further concluded that the laser welding process can provide welds with properties equivalent to, or better than, the material in which they are formed and can be generated at high speed with a minimum of thermal energy input and distortion. Finally, it is concluded that relatively straightforward pre-weld cleaning techniques and gas-shielding provisions can effectively eliminate atmospheric contamination in welds formed in the subject materials.

Further experimental investigations are desirable to advance the state of the art in this highly promising area; specifically, it is recommended that:

1. Laser welding tests be continued in high-yield-strength steels with principal attention directed toward the process of weld metal refinement during the welding process. Emphasis should be placed on establishment of conditions for attainment of maximum zone refinement and anticipated maximum improvement in weld zone strength and ductility.

2. Laser welding tests in titanium alloy be continued and expanded to include alloys other than Ti-6Al-4V. Specific attention should be directed toward

phase transformations and grain growth during welding and their effects on weld properties. Attempts should be made to reduce weld spatter and to improve weld bead characteristics. Mechanical testing should be extended to include fatigue endurance properties.

3. Laser welding tests in aluminum alloys should be continued and extended to include important, heat-treatable alloys. With respect to the latter, utilization of preplaced, or continuously-added, filler material and its effect on weld properties should be investigated. Emphasis should be placed on establishment of welding procedures for repeatable generation of high-quality, nonporous welds.

ACKNOWLEDGEMENT

The assistance of Dr. E. M. Breinan of UARL in providing X-ray, metallurgical, and mechanical evaluation of welds is gratefully acknowledged.

REFERENCES

1. Brown, C. O. and J. W. Davis: The Coaxial Electric-Discharge Convection Laser. United Aircraft Research Laboratories Report UAR-J251, October 1970.

2. Brown, C. O. and J. W. Davis: Investigation of a Multikilowatt CO_2 Cross-Beam Convection Laser. Paper presented at the Fifth DOD Conference on Laser Technology, Monterey, California, April 25-27, 1972.

3. Brown, C. O. and C. M. Banas: Deep Penetration Laser Welding. Paper presented at the American Welding Society 52nd Annual Meeting, San Francisco, California, April 26-29, 1971.

4. Banas, C. M., A. P. Walch and C. O. Brown: Materials Processing with Carbon-Dioxide Lasers. Paper presented at the IEEE Eleventh Symposium on Electron, Ion and Laser Beam Technology, Boulder, Colorado, May 12-14, 1971.

5. Banas, C. M.: Laser Welding Developments. Invited paper presented at the CEGB International Conference on Welding Related to Power Plants, Southampton, England, September 18-21, 1972.

6. Locke, E. V., E. D. Hoag and R. A. Hella: Deep Penetration Welding with High Power CO_2 Lasers. Welding Journal, Vol. 51, No. 5, pp. 245s-249s, May 1972.

7. Banas, C. M. and R. W. Lessard: Evaluation of CO_2 Laser Welding in Rimmed Sheet Steel. United Aircraft Research Laboratories Report UAR-K158, December 1971.

8. Breinan, E. M. and C. M. Banas: Laser Weld Characteristics in HY-130 Steel (Controlled). United Aircraft Research Laboratories Report M110087-1, September 1973.

TABLE I

WELD MATERIAL CHARACTERISTICS

5456 Aluminum

Designation:	Alcoa Ht No. 692521	
Thickness:	1/8 in.	
Composition:	Si & Fe:	0.40 max
	Cu:	0.10 max
	Mn:	1.0/1.15
	Mg:	4.7/5.5
	Cr:	0.05/0.2
	Zn:	0.25 max
	Ti:	0.20 max
	Others:	Each: 0.05 max
	Total:	0.15 max
Tensile Strength:	54,000-53,300 psi	
Yield Strength:	42,800-41,900 psi	
Elongation (2 in.)	10.0 - 9.0%	

HY-130 Steel

Designation:	Ht No. 5P4755	
Thickness:	1/4 in.	
Composition:	C:	0.11
	Mn:	0.80
	P:	0.005
	S:	0.007
	Si:	0.30
	Ni:	4.89
	Cr:	0.52
	Mo:	0.49
	V:	0.054
	Ti:	0.002
	Cu:	0.06

TABLE I
(cont'd)

Heat treatment:	1525°F - 49 min 1160°F - 39 min	
Tensile Strength:	150,800-150,800 psi	
Yield Strength:	144,500-142,900 psi	
Elongation:	16.5% - 17.0%	
Reduction in Area:	63.2% - 55.0%	

Titanium 6Al-4V

Designation:		
Thickness:	1/8 in. and 1/4 in.	
Composition:	Al:	5,500-6,750
	V:	3,500-4,500
	Fe:	0.30 max
	C:	0.10 max
	N:	0.07 max
	H:	0.015 max
	O:	0.20 max
	Other:	0.40 max
Tensile Strength:	130,000 psi	
Yield Strength:	120,000 psi	
Elongation:	8.0%	

TABLE I
(cont'd)

HY-180 Steel

Designation:	Ht. No. 3811304	
Thickness:	1/16 in.	
Composition:	C:	0.18
	Mn:	0.23
	P:	0.010
	S:	0.006
	Si:	0.050
	Cu:	0.15
	Ni:	9.29
	Cr:	0.80
	Mo:	0.96
	V:	0.09
	Co:	4.55
Tensile Strength:	199,500 psi	
Yield Strength:	183,600 psi	
Elongation:	10%	
Hardness:	R_c:	36

TABLE II

LASER WELDING TEST PARAMETERS

Bead-on-Plate Penetrations

Test No.	Material	Laser Power (kW)	Speed (ipm)	Comment
C0313-1	HY-180	5	180	
-2	"	"	160	
-3	"	"	140	
-4	"	"	120	
-5	HY-130	"	60	Incomplete penetration
-6	"	"	50	
-7	"	"	40	
-8	"	"	30	Nonuniform
-9	Ti-6Al-4V($\frac{1}{4}$)*	"	50	
-10	"	"	60	
-11	"	"	70	
-12	"	"	40	
-13	Ti-6Al-4V($\frac{1}{8}$)	"	80	
-14	"	"	100	
-15	"	"	120	
-16	"	"	140	
-17	5456 Al	"	140	
-18	"	"	120	
-19	"	"	120	Change in shield gas flow
-20	"	"	120	
C0314-1	5456 Al	"	120	Variation in shielding
-2	"	"	"	"
-3	"	"	"	"
-4	"	"	"	"
-5	"	"	"	"
-6	"	"	"	"
-7	"	"	"	
-8	"	"	140	
-9	5456-Al	5.7	180	
-10	"	"	160	
-11	"	"	140	
-12	HY-180	3.5	100	

TABLE II
(cont'd)

Test No.	Material	Laser Power (kW)	Speed (ipm)	Comment
C0314-13	HY-180	3.5	120	No shield gas
-14	"	"	120	
-15	"	"	140	
-16	"	"	160	
-17	HY-130	"	40	
-18	"	"	30	
-19	"	"	25	
-20	"	"	20	Shield moved
C0315-1	Ti-6Al-4V($\frac{1}{8}$)	3.5	80	
-2	"	"	100	
-3	"	"	60	
-4	"	"	40	
-5	Ti-6Al-4V($\frac{1}{4}$)	"	40	
-6	"	"	30	
-7	"	"	20	
-8	"	"	25	
C0316-1	HY-180	2.0	50	
-2	"	"	60	
-3	"	"	40	
-4	"	"	30	
-5	Ti-6Al-4V($\frac{1}{8}$)	"	20	Deep penetration
-6	"	"	25	Mode breakdown?
-8	"	"	40	
C0525-1	HY-130	8.0	70	Full penetration
-2	Ti-6Al-4V($\frac{1}{4}$)	"	70	"
-3	5456 Al	"	180	"
-4	Ti-6Al-4V($\frac{1}{8}$)	"	130	Good bead characteristics

*Titanium alloy bead-on-plate specimens were stress-relieved at 1000°F for 2 hours in air. Weld beads in the other materials are in the "as-welded" condition.

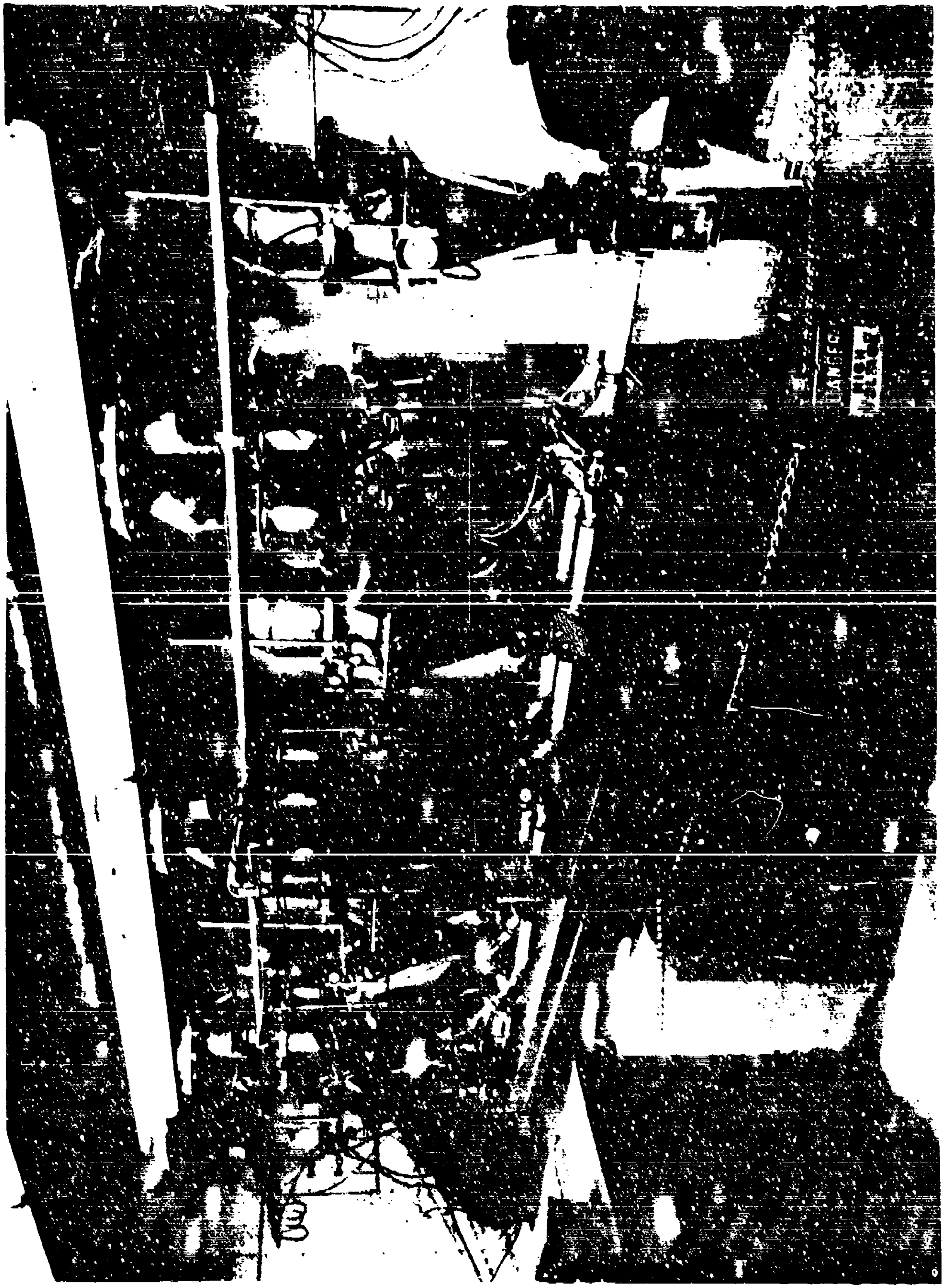
TABLE III

LASER WELDING TEST PARAMETERS

Demonstration Welds

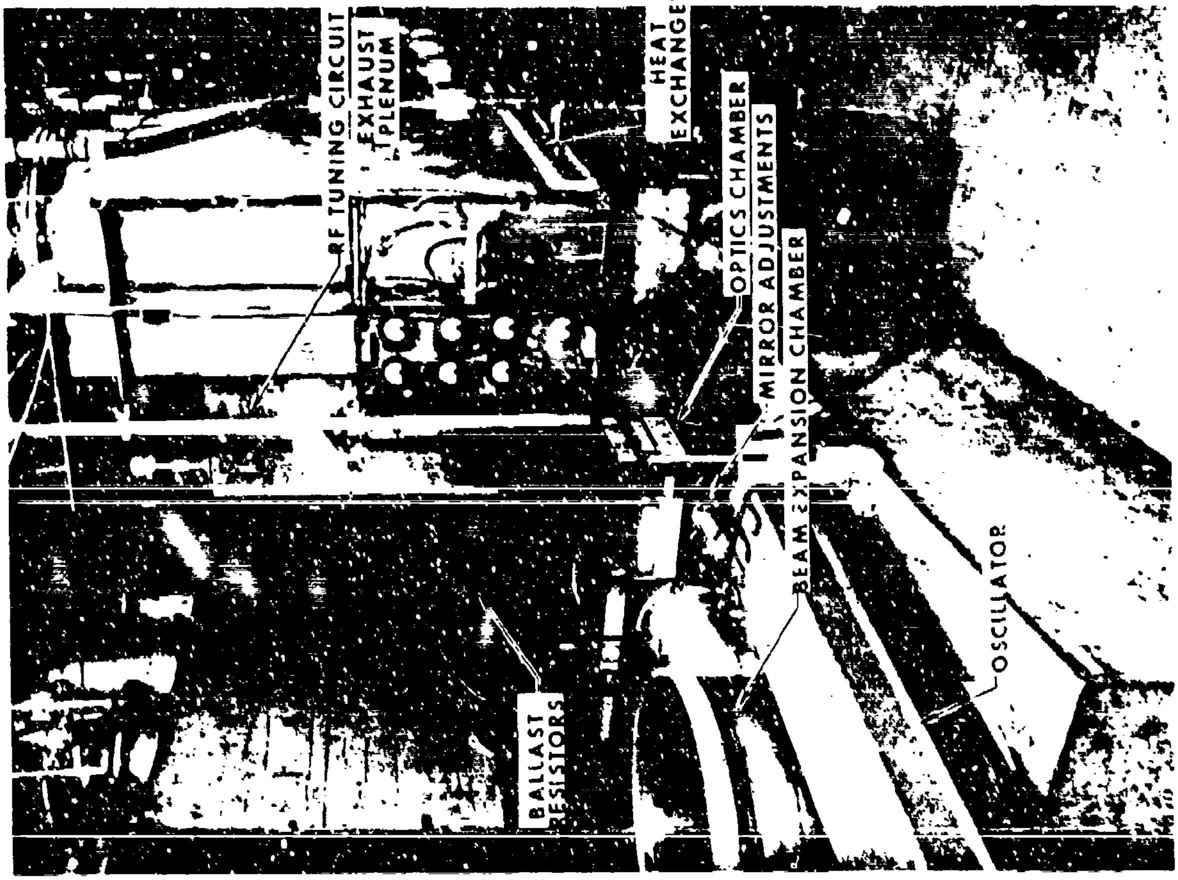
Material	Thickness (in.)	Weld Type	Laser Power (kW)	Weld Speed (ipm)	No. of Pieces	Ref. Fig.
HY-130 Steel	1/4	Butt	5.5	50	3	8
HY-180 Steel	1/16	Butt	5.5	160	2	9
HY-180 Steel	1/16	Lap	5.5	140	1	10
Ti-6Al-4V	1/4	Butt	5.5	50	2	11
Ti-6Al-4V	1/8	Butt	5.5	100	2	12
5456 Al	1/8	Butt	5.5	100	2	13

Note: Titanium alloy specimens were stress-relieved at 1000°F for two hours in vacuum; the other specimens were in the as-welded condition. All specimens were welded with argon shielding.

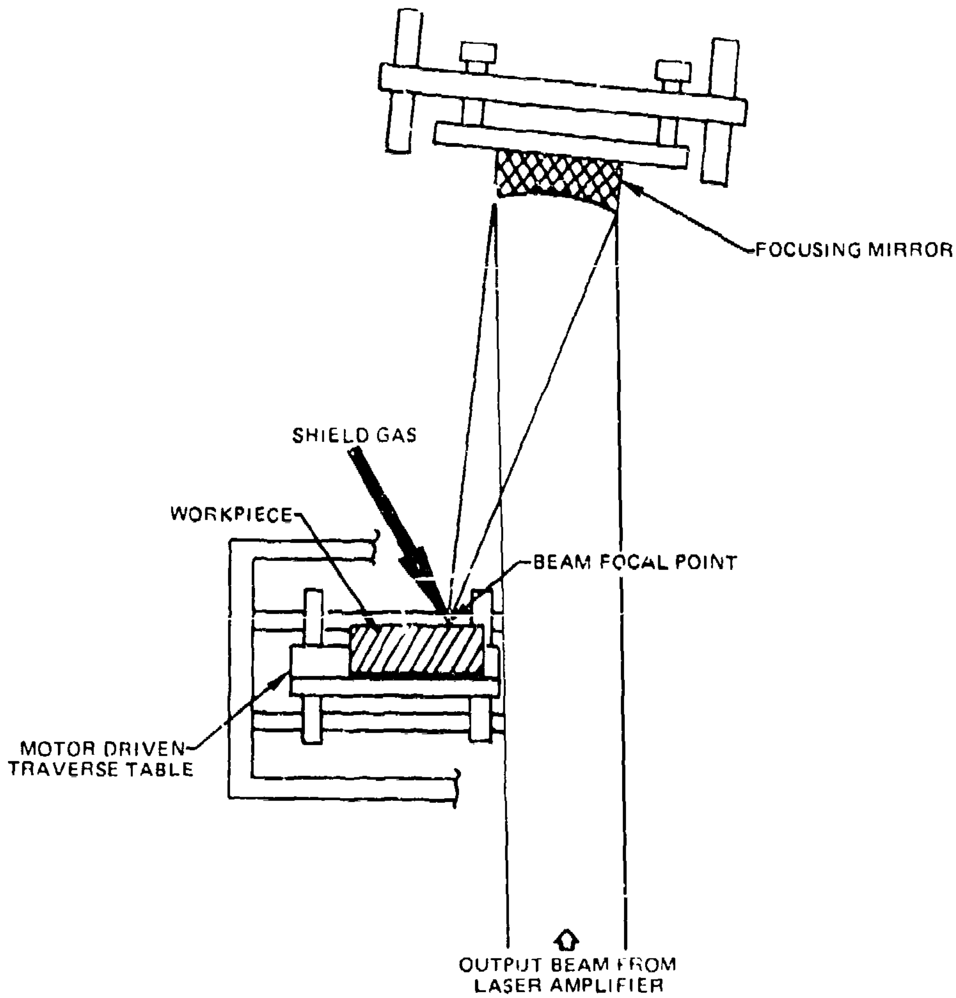


6 kW LASER INSTALLATION

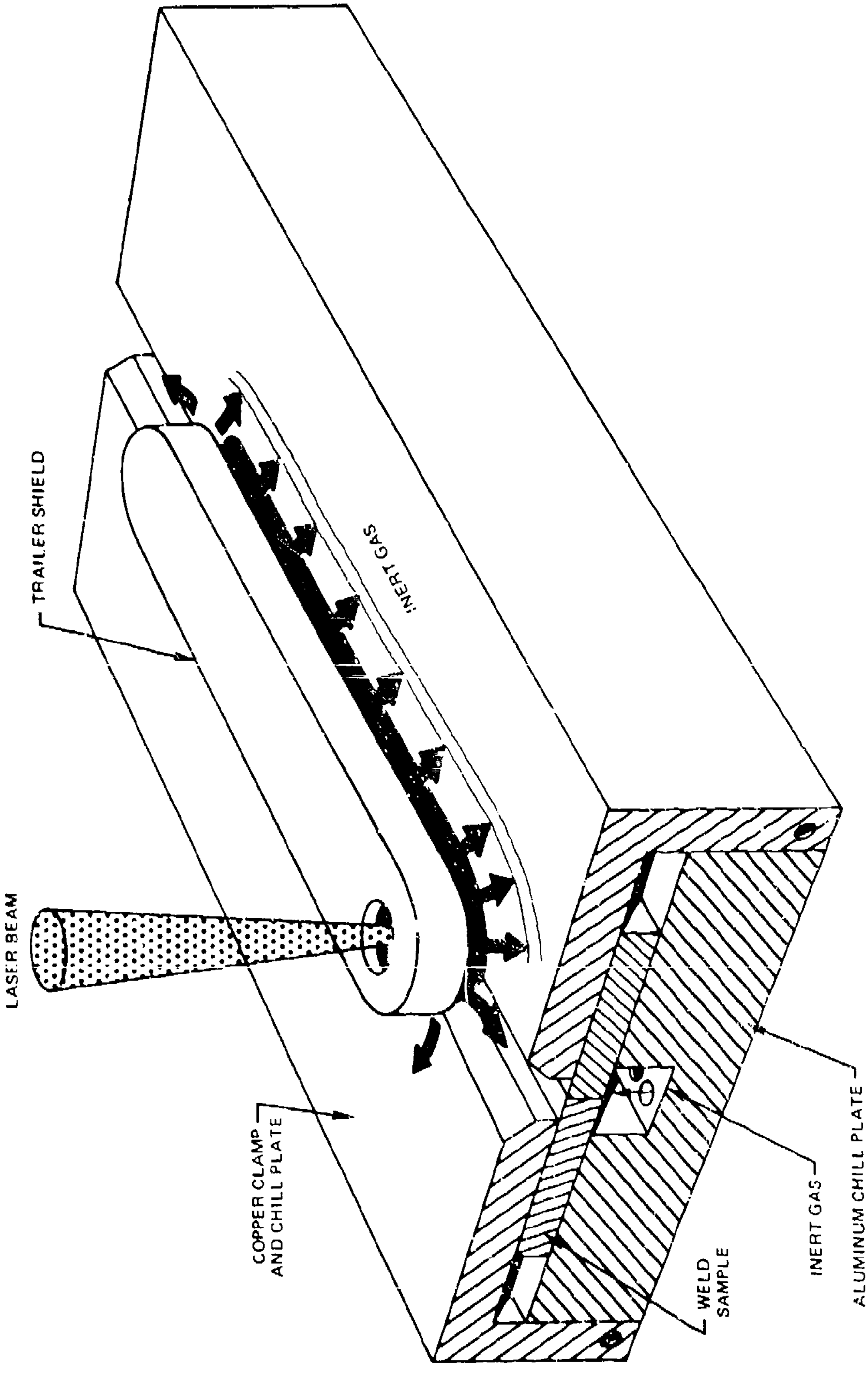
HIGH POWER LASER INSTALLATION



PLAN VIEW OF DEEP PENETRATION WELDING APPARATUS



GAS SHIELD CONFIGURATION



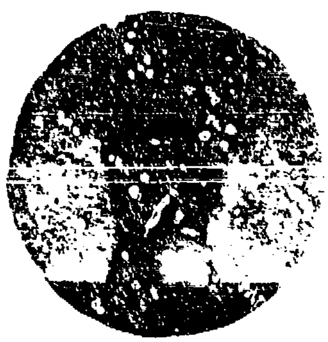
EFFECT OF SPEED ON WELD CHARACTERISTICS

5456 ALUMINUM ALLOY

5 kW

0.1 IN.

180 ipm



160 ipm

140 ipm

120 ipm

BUTT WELD CHARACTERISTICS

MATERIAL: HY-180 STEEL
THICKNESS 0.063 IN.
LASER POWER 5.0 kW
WELD SPEED: 140 ipm

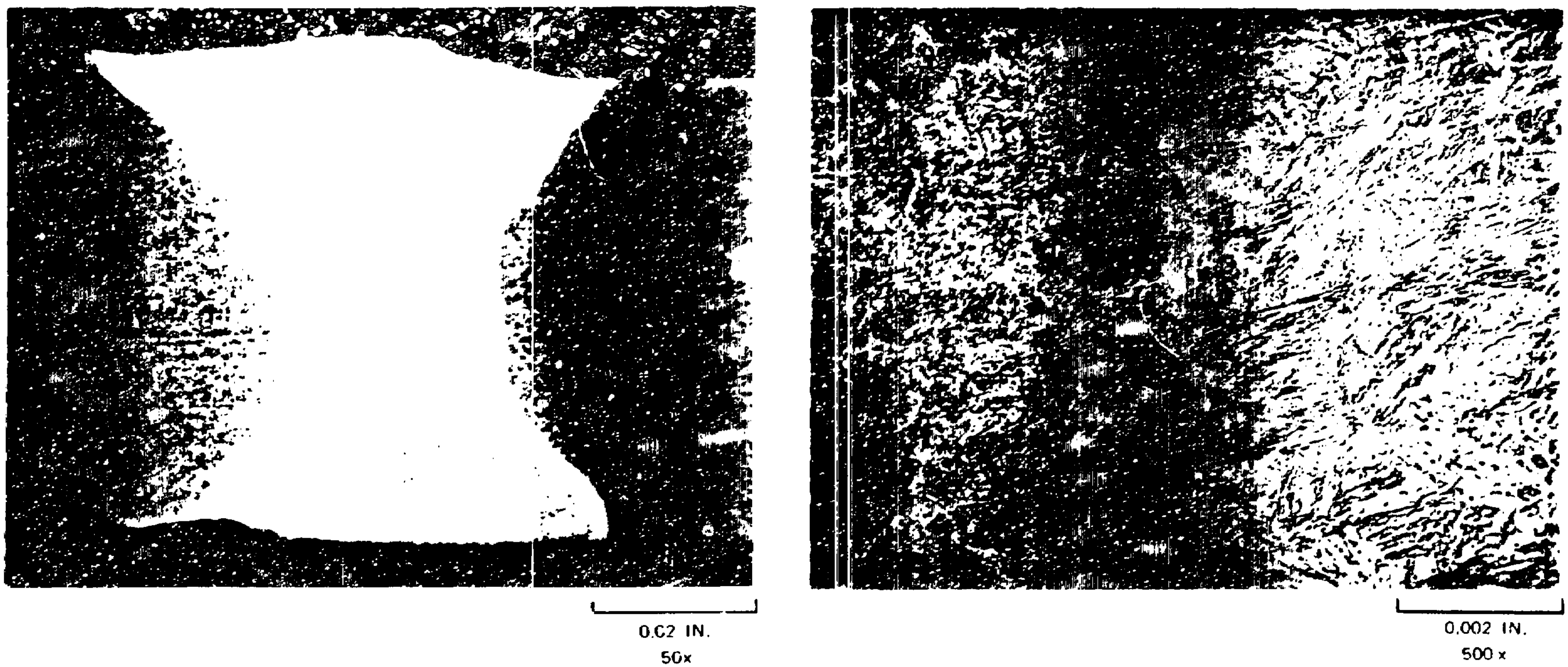
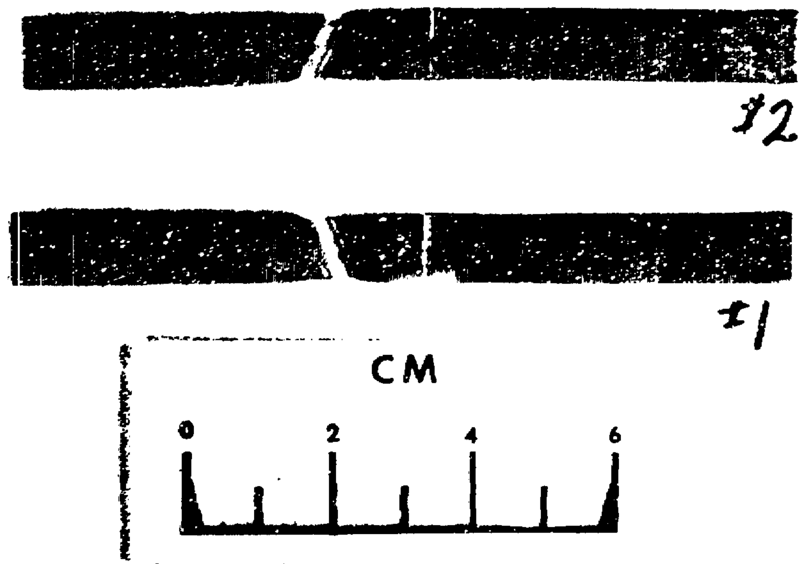


FIG. 6

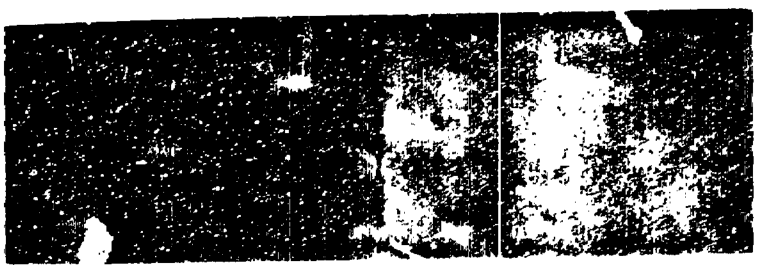
BUTT WELD CHARACTERISTICS

MATERIAL: HY-180 STEEL
THICKNESS: 0.063 IN.
LASER POWER: 5.0 kW
WELD SPEED: 140 ipm



TENSILE TEST SPECIMENS

FAILURE STRESS
#1 167,400 psi
#2 166,000 psi



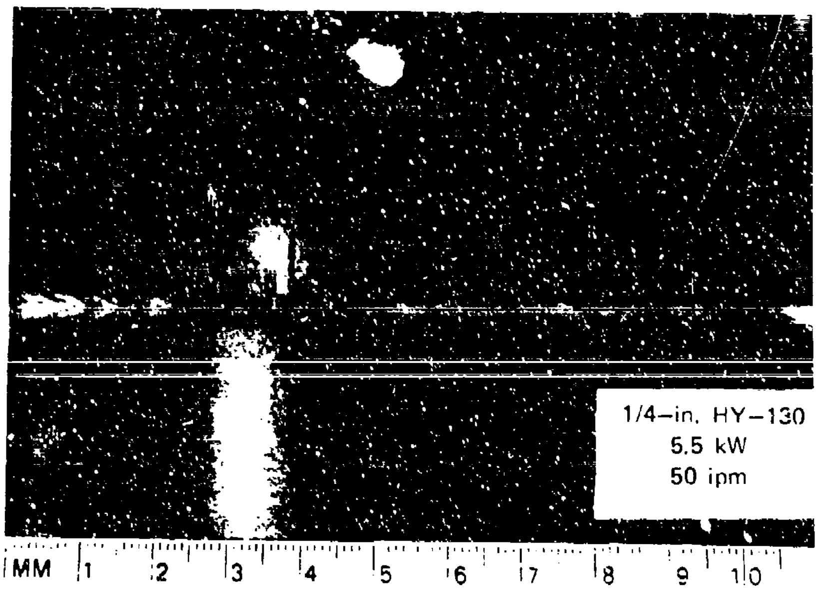
X-RAY SPECIMEN

FIG. 7

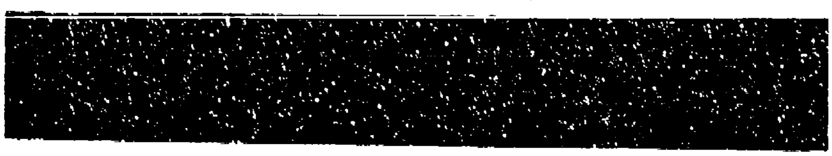
FIG. 8

BUTT WELD SAMPLE

WELD BEAD CHARACTERISTICS

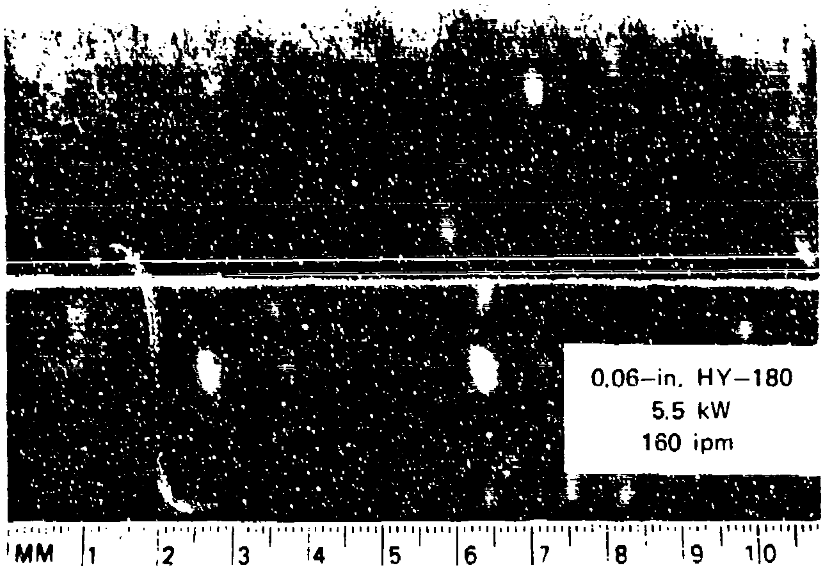


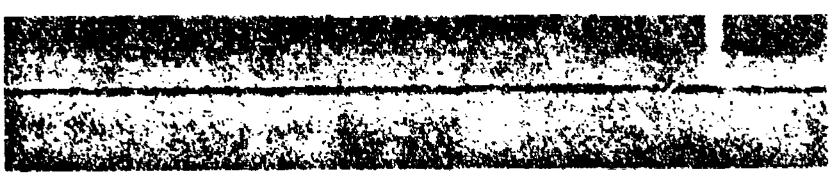
X-RAY CHARACTERISTICS



BUTT WELD SAMPLE

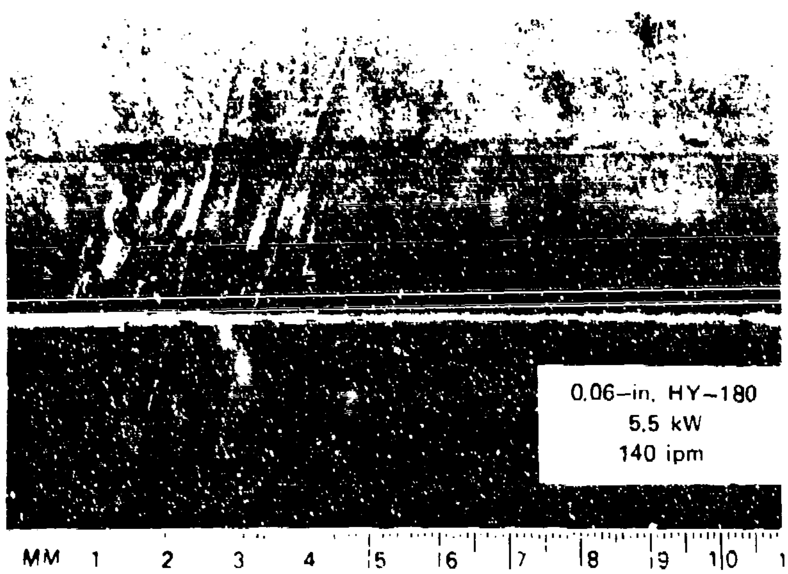
WELD BEAD CHARACTERISTICS



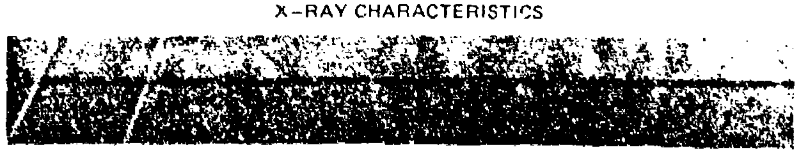


LAP WELD SAMPLE

WELD BEAD CHARACTERISTICS

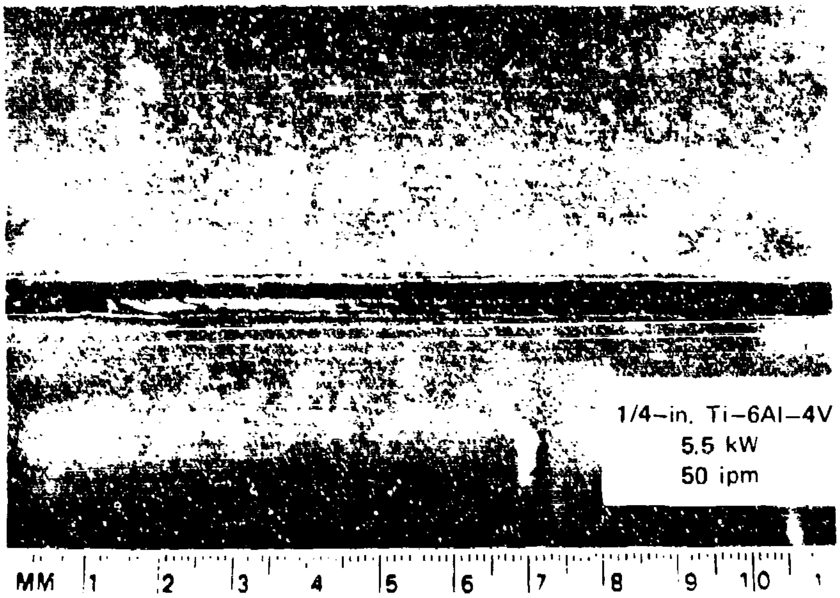


X–RAY CHARACTERISTICS



BUTT WELD SAMPLE

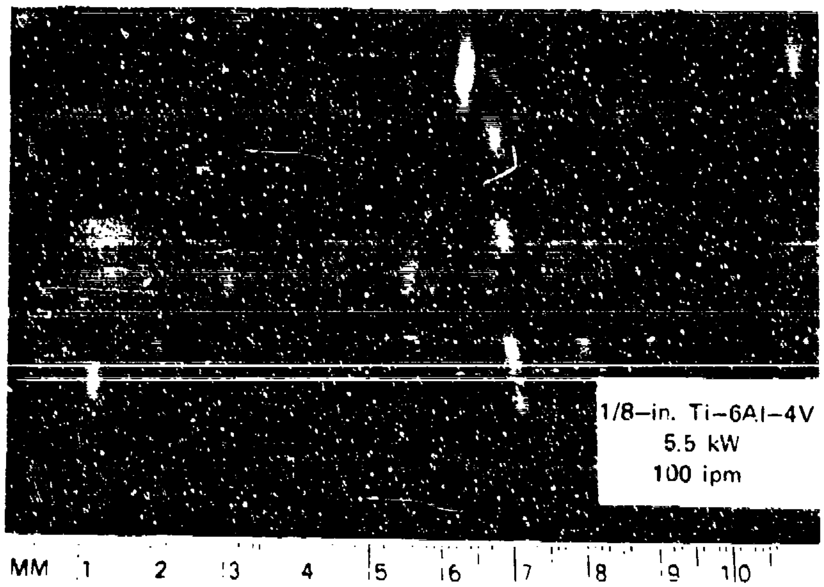
WELD BEAD CHARACTERISTICS



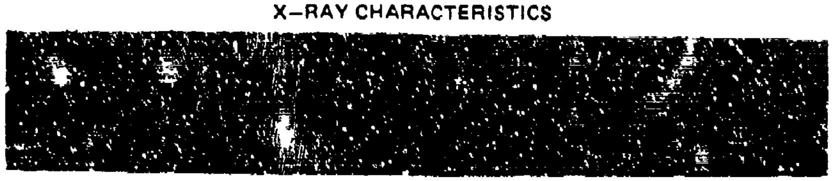
X-RAY CHARACTERISTICS

BUTT WELD SAMPLE

WELD BEAD CHARACTERISTICS

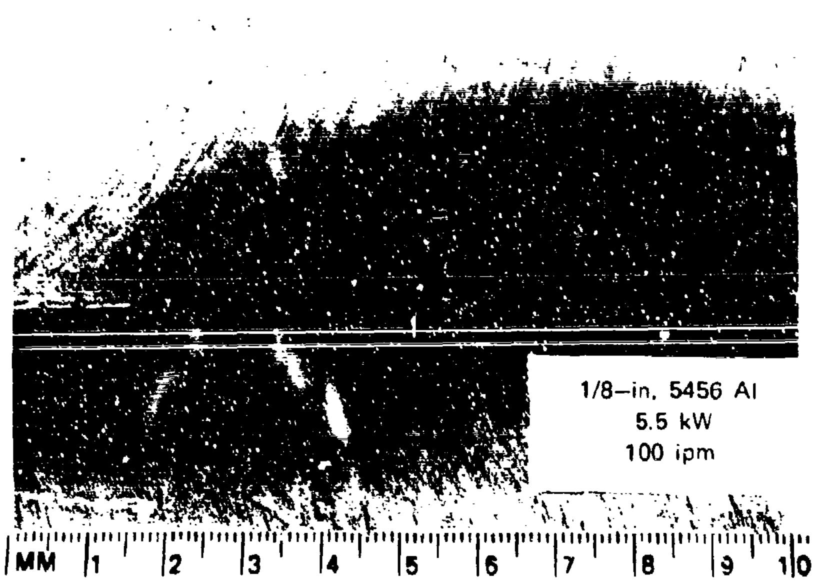


X-RAY CHARACTERISTICS



BUTT WELD SAMPLE

WELD BEAD CHARACTERISTICS



X-RAY CHARACTERISTICS